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Study and Design of an Autonomous Fire-Fighting robot with an Extinguisher.

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Abstract**—** Fire incidents pose a significant threat to both urban and wild land environments worldwide. Preventing and combating fires require the employment of effective and safe technologies. Primitive techniques of extinguishing fires usually consisted of manual interventions or using natural resources, which often resulted in limited efficiency and inadequate protection for human firefighters. In this context, the development of an autonomous fire-fighting robot, equipped with the Robot Operating System (ROS) and autonomous navigation systems, offers a solution to minimize the risks faced by firefighters and optimize response times. This project focuses on a fully autonomous system designed to detect and suppress fires, particularly in industrial environments where the fire risk is heightened.

Keywords**—** Fire-Fighting, Robotics, ROS, CAD, Autonomous Systems.

I. INTRODUCTION

Fire is one of the most destructive forces known to humankind, and nowhere is its threat more evident than in industrial and storage facilities, where valuable goods and resources are housed in large quantities. A single fire can destroy not only millions of dollars worth of materials but also cause irreversible damage to human lives, businesses, and the environment. As modern societies continue to expand their industrial capabilities and increase their reliance on large-scale storage facilities, the need for more effective fire prevention and suppression systems has never been more critical.

Between 2016 and 2020, there were, on average, 1,410 fires annually in storage facilities in the United States, causing more than $250 million in property damage each year [1]. These fires often occur in environments where flammable materials are stored, making them especially dangerous and difficult to control. In many cases, by the time human firefighters are able to respond, the fire has already spread beyond control, leading to catastrophic losses. This ongoing threat calls for innovative solutions that can prevent, detect, and mitigate fires faster than traditional methods.

In light of alarming statistics, the development of autonomous fire-fighting robots emerges as a groundbreaking advancement in fire safety technology. Unlike conventional firefighting approaches, these robots are engineered to function in the most perilous conditions, effectively combating fires while safeguarding human lives. Outfitted with state-of-the-art sensors, robust extinguishing systems, and autonomous navigation, these robots can locate and suppress fires without direct human intervention. Their ability to combine speed, precision, and autonomy makes them invaluable in fire prevention and suppression, particularly in industrial settings where fires can escalate rapidly and unpredictably [2].

One of the most significant benefits of autonomous fire-fighting robots is their capacity to operate continuously in dangerous environments. These robots are specifically designed to navigate complex areas, such as warehouses and depots, where narrow aisles, dense storage, and hazardous materials pose significant challenges for human firefighters. By utilizing advanced sensors like LiDAR, infrared cameras, and gas detectors, the robots can detect fires early, often before they become visible. Their autonomous navigation systems enable them to move through cluttered spaces with precision, allowing them to reach fire hotspots that may be difficult or life-threatening for human responders to access.

The integration of artificial intelligence (AI) and real-time data processing further enhances the operational efficiency of these robots. By constantly monitoring environmental conditions, they can assess the severity of a fire, determine the optimal firefighting strategy, and deploy suppression systems, such as CO_2 or water, with pinpoint accuracy. This not only reduces the time it takes to extinguish a fire but also minimizes the potential for collateral damage. Additionally, the robots provide critical real-time data to human firefighters, enabling them to make more informed decisions about how to manage the situation effectively [3].

The importance of this innovation cannot be overstated. Fire incidents in storage facilities and industrial depots are a global concern, with significant economic and human repercussions. In regions where fire safety measures are less stringent, the risks are even greater. While human firefighters remain essential to fire management, the introduction of autonomous systems offers a transformative new tool in the fight against this ever-present threat. By reducing response times, minimizing exposure to dangerous conditions, and enhancing the overall effectiveness of fire suppression efforts, autonomous fire-fighting robots represent the future of fire safety.

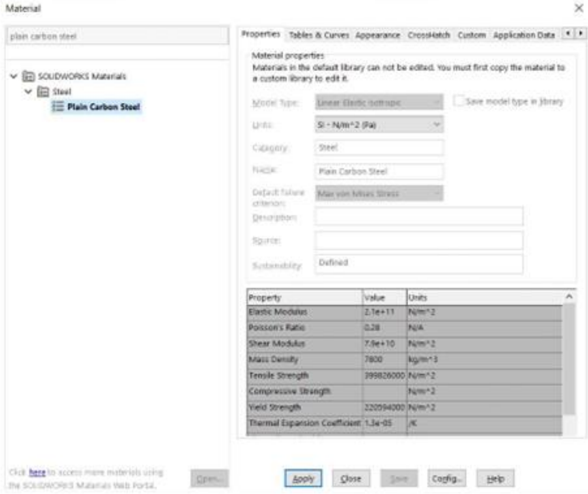
The conclusion of this thesis will summarize the main findings from each chapter and reflect on the overall contributions of the project to the field of autonomous fire-fighting robots.

Through this research, the project aims to contribute to the growing body of knowledge on autonomous fire-fighting systems and their applications in industrial and storage environments. By addressing both the technical challenges and the real-world implications of fire safety, this thesis seeks to lay the groundwork for a new era of fire prevention and suppression technologies that prioritize both efficiency and human safety.

II. Design and Architecture:

The robot's design is divided into three main assemblies, each playing a crucial role in its functionality. The base consists of the robot body, which is built around a tubular frame covered by external panels on all sides. The tubular frame was designed using a 3D sketch and the weldment feature in SolidWorks, with a tube section of 20x20 mm. Plain carbon steel was selected for the frame due to its excellent mechanical properties, making it ideal for structural applications in fire-fighting environments.

The attached panels not only provide additional structural integrity but also house various critical components of the robot, ensuring protection and accessibility. These panels are carefully aligned to maintain the robot's stability and functionality under the harsh conditions of a fire-fighting scenario.



Material properties
Materials in the default library can not be edited. You must first copy the material to a custom library to edit it.

Model Type: Linear Elastic Isotropic
Units: SI - N/m^2 (Pa)
Category: Steel
Name: Plain Carbon Steel
Default failure criterion: Max von Mises Stress
Description:
Source:
Sustainability: Defined

Property	Value	Units
Elastic Modulus	2.1e+11	N/m^2
Poisson's Ratio	0.28	N/A
Shear Modulus	7.9e+10	N/m^2
Mass Density	7800	kg/m^3
Tensile Strength	399826000	N/m^2
Compressive Strength		N/m^2
Yield Strength	220594000	N/m^2
Thermal Expansion Coefficient	1.3e-05	/K

Click here to access more materials using the SOLIDWORKS Materials Web Portal.

Figure 1: Plain carbon steel properties.

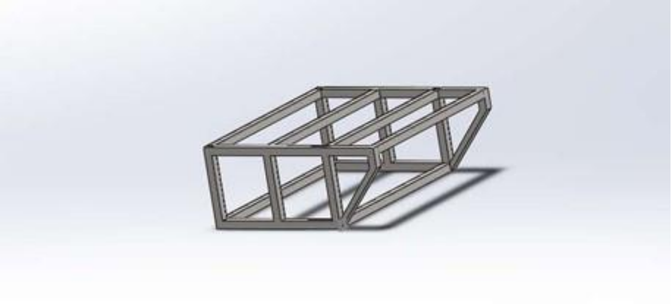


Figure 2: Tubular frame design in SolidWorks.

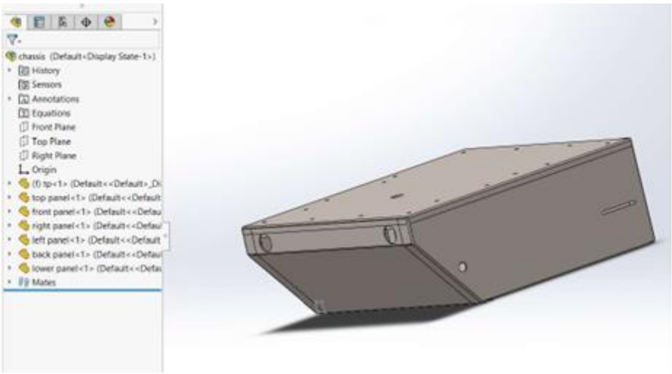


Figure 3: Full assembly of the tubular frame and panels forming the body.

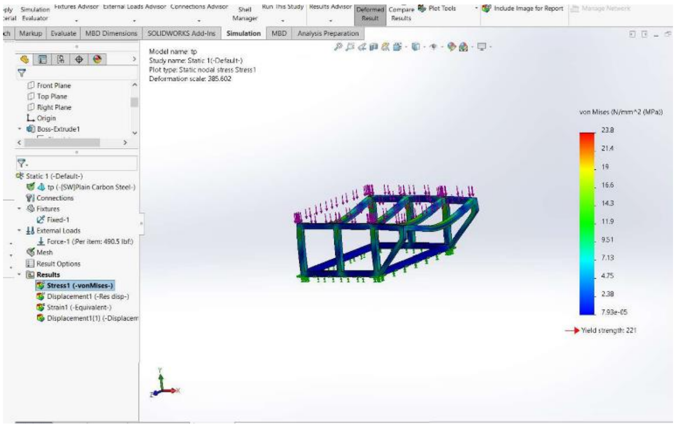
After designing the tubular frame, we applied the load conditions to see if the structure is strong enough. So the force generated by the weight of the fire-fighting equipment assumed to be 50 kg, the equivalent force is calculated using the following equation:

$F = m.g$

Where :

- F is the force applied (in newtons)
- m is the equipment weight
- g is the acceleration due to gravity ($9.81\ m/s^2$)

$$F = 50 \times 9.81 = 490.5\ N$$



Model name: tp
Study name: Static 1(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 385.602

Figure 4: Plain carbon steel properties.

The Von Mises stress distribution identifies areas of maximum stress on the frame. The maximum stress experienced by the structure was 23.8 MPa. significantly below the yield strength of 220 MPa. confirming the frame's integrity under the applied load. Figure III.5 illustrates the stress distribution.

Transmission System Design :

In designing our fire-fighting robot, we chose tracked mobility after evaluating wheeled, legged, and aerial options, as it best meets the demands of fire-fighting. Tracked mobility offers excellent adaptability to challenging environments, such as uneven or debris-filled surfaces, by evenly distributing the robot's weight and maintaining stability. The large contact area ensures strong traction, even on slippery terrain. Tracked systems are also more robust and durable, with fewer exposed moving parts, reducing the risk of failure in extreme conditions. Though slower than wheeled systems, their stability, ability to overcome obstacles, and operational efficiency make tracked robots highly effective in fire-fighting scenarios.

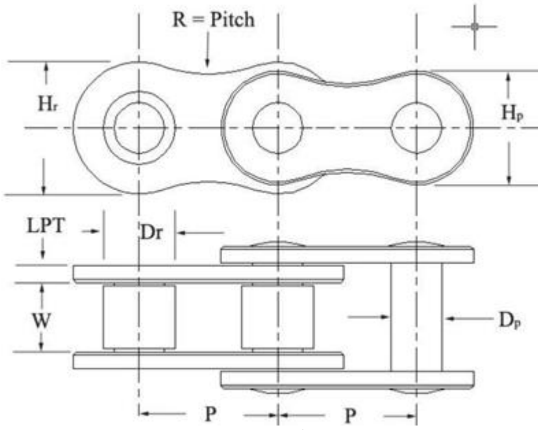


Figure 5: Chain link dimensions definition**.**

The process of selecting the roller chain for the fire-fighting robot began by calculating the total gravitational force, considering the robot's mass of 100 kg. With two drive chains sharing the load, each chain was required to support 490.5 N. A safety factor of 3 was applied, meaning each chain needed to withstand at least 1,471.5 N. After reviewing various options, the ISO 08B roller chain was chosen for its tensile strength of 10,900 N, which far exceeded the required value, ensuring durability and reliability during operation.

$$F_{\text{gravity}} = m \times g$$

$$F_{\text{gravity}} = 100\,\text{kg} \times 9.81\,\text{m/s}^2 = 981\,\text{N}$$

$$F_{\text{per\_chain}} = \frac{981\,\text{N}}{2} = 490.5\,\text{N}$$

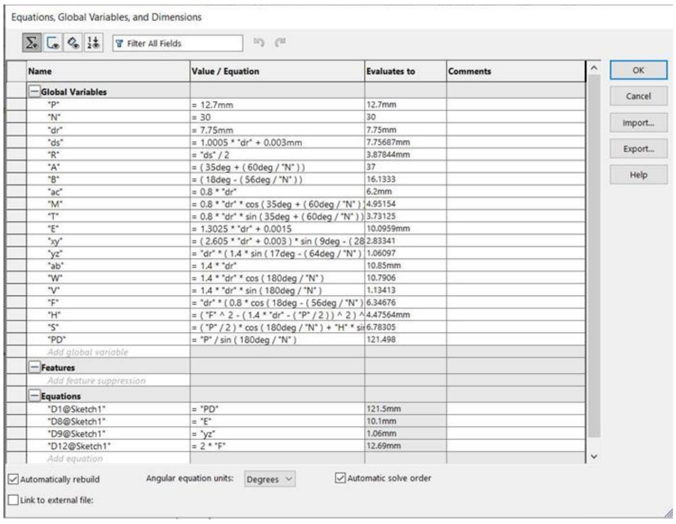
$$F_{\text{safe}} = F_{\text{per\_chain}} \times S_f$$

$$F_{\text{safe}} = 490.5\,\text{N} \times 3 = 1,471.5\,\text{N}$$

Dimension	Symbol	Value
Pitch	P	12.7 mm
Width	W	7.79 mm
Roller Diameter	D_r	7.75 mm
Link Plate Thickness	LPT	1.5 mm
Pin Diameter	D_p	4.45 mm
Inner Height	H_r	11.3 mm
Outer Height	H_p	11.81 mm

Table 1: Roller chain dimensions.

The sprocket design process began by selecting the pitch of the ISO 08B roller chain, which is 12.7 mm, and determining the number of teeth, set to 30. Using these parameters, the pitch diameter was calculated to be approximately 121.52 mm. Next, the material for the sprocket was chosen, with steel being selected for its strength and durability in industrial environments. The outside diameter of the sprocket was then calculated to be around 129.41 mm. Parametric design in SolidWorks was employed to ensure that all dimensions and features, such as the tooth profile and spacing, were automatically updated based on the selected variables, streamlining the design process.



Name	Value / Equation	Evaluates to	Comments
Global Variables			
"P"	= 12.7mm	12.7mm	
"N"	= 30	30	
"dr"	= 7.75mm	7.75mm	
"ds"	= 1.0005 * "dr" + 0.003mm	7.75687mm	
"R"	= "ds" / 2	3.87844mm	
"A"	= (35deg + (60deg / "N"))	37	
"B"	= (18deg - (56deg / "N"))	16.1333	
"ac"	= 0.8 * "dr"	6.2mm	
"M"	= 0.8 * "dr" * cos (35deg + (60deg / "N")	4.95154	
"T"	= 0.8 * "dr" * sin (35deg + (60deg / "N"))	3.73125	
"E"	= 1.3025 * "dr" + 0.0015	10.0959mm	
"xy"	= (2.605 * "dr" + 0.003) * sin (9deg - (28	2.83341	
"yz"	= "dr" * (1.4 * sin (17deg - (64deg / "N")	1.06097	
"ab"	= 1.4 * "dr"	10.85mm	
"W"	= 1.4 * "dr" * cos (180deg / "N")	10.7906	
"V"	= 1.4 * "dr" * sin (180deg / "N")	1.13413	
"F"	= "dr" * (0.8 * cos (18deg - (56deg / "N")	6.34676	
"H"	= ("F" ^ 2 - (1.4 * "dr" - ("P" / 2)) ^ 2) ^	4.47564mm	
"S"	= ("P" / 2) * cos (180deg / "N") + "H" * si	6.78305	
"PD"	= "P" / sin (180deg / "N")	121.498	
Add global variable			
Features			
Add feature suppression			
Equations			
"D1@Sketch1"	= "PD"	121.5mm	
"D8@Sketch1"	= "E"	10.1mm	
"D9@Sketch1"	= "yz"	1.06mm	
"D12@Sketch1"	= 2 * "F"	12.69mm	
Add equation			

☑ Automatically rebuild
Angular equation units: Degrees
☑ Automatic solve order
☐ Link to external file:

Figure 6: Sprocket equations implementation in SolidWorks.

Figure 7: Sprocket design in SolidWorks.

We also designed a tensioner to ensure proper tension in the transmission system. The design consists of a base support plate, two wheels, and an axle that allows smooth rotation of the wheels. The base plate was extruded to provide a solid foundation for mounting the tensioner, while the wheels were modeled with bearings to minimize friction and ensure efficient rotation.

Figure 8: Tensioner design in SolidWorks.

Next, we designed the suspension system, which consists of the shock absorber, support arms. and wheels. The arms were designed to attach the wheels to the robot's main body and allow the shock absorbers to provide the necessary flexibility. The wheels were positioned on axles and aligned to ensure that they would move together smoothly.

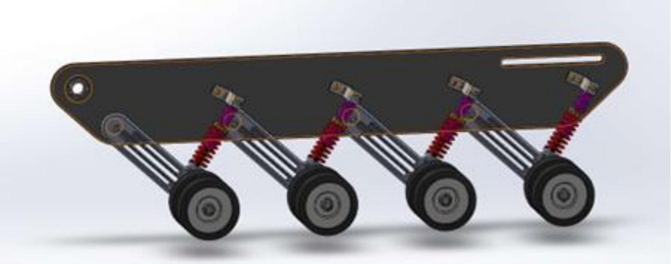


Figure 8: Suspension system assembly.

After designing and assembling all individual components, including the suspension system, shock absorbers, wheels, and chain system, the entire transmission system was integrated into the robot's structure. This final assembly ensures that the robot can effectively navigate rugged terrains while maintaining stability and traction.
The image below shows the complete transmission system assembly, which includes the drive sprocket, suspension system, and continuous track, demonstrating how all the components work together to provide efficient movement over different surfaces.

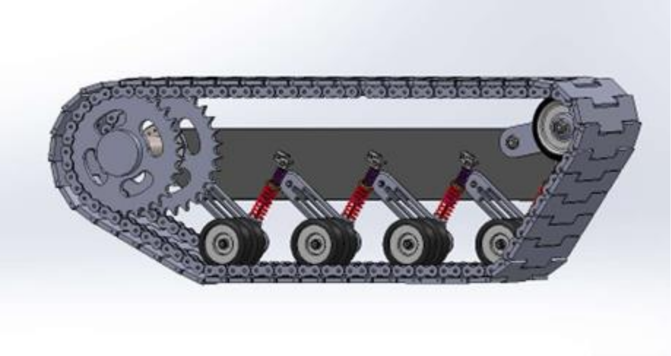


Figure 10: Final assembly of the transmission system.

Fire Suppression System :

The fire suppression system is a critical part of the fire-fighting robot, responsible for carrying out fire-fighting missions. Its primary components include the extinguishers and the monitor, which work together to suppress the fire. The extinguishers release the extinguishing agent, which is directed through a pipe system to the monitor, where it is then aimed at the fire. Supporting components such as the extinguisher bracket, electric valve, and pipes play essential roles in ensuring the system functions effectively. The extinguisher bracket securely holds the extinguisher in place during operation, preventing any movement that could disrupt the flow. The electric valve controls the release of the extinguishing agent, allowing precise regulation of flow based on the situation. The pipes transport the agent from the extinguisher to the monitor, ensuring smooth and uninterrupted delivery during fire suppression.

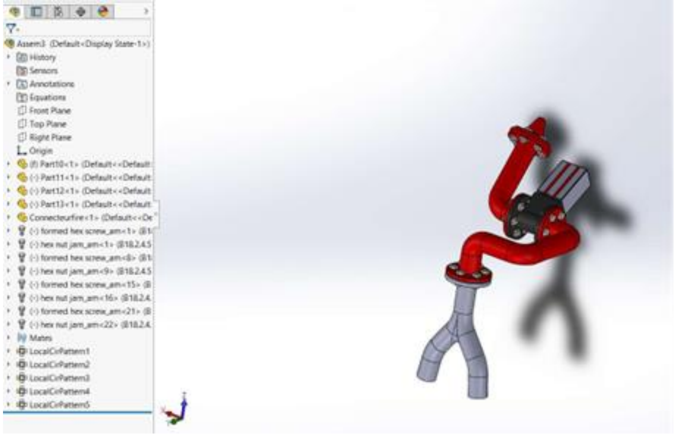


Figure 11: Fire-fighting monitor design.

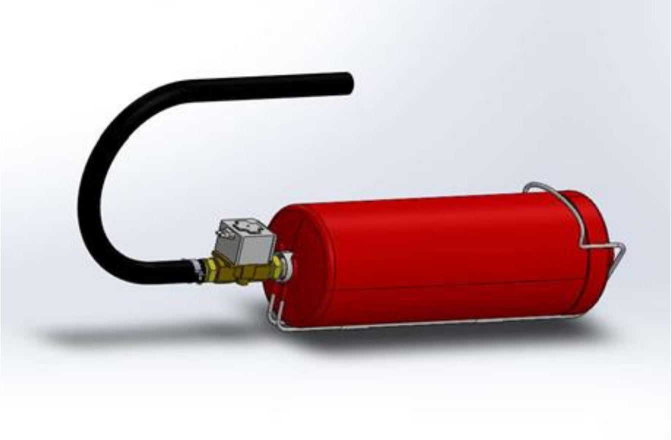


Figure 12: CO2 extinguisher, Bracket, electric valve and pipe assembly.

The assembly of the fire-fighting robot begins with the tubular frame, which provides structural integrity and stability for all major components during movement and fire-fighting operations. Once the frame is in place, protective panels are attached, enclosing the internal components while adding rigidity and ensuring easy maintenance. After the frame and panels are assembled, the transmission system, which includes the tracked mobility mechanism, roller chains, and sprockets, is integrated to allow the robot to traverse challenging terrains. The CO2 fire-fighting monitor is then installed for precise vertical movement, enabling targeted fire suppression. Finally, the CO2 extinguisher, support structure, and electrovane are assembled, allowing precise control of the CO2 flow. The completed robot is a compact, efficient machine capable of tackling fires in hazardous environments.

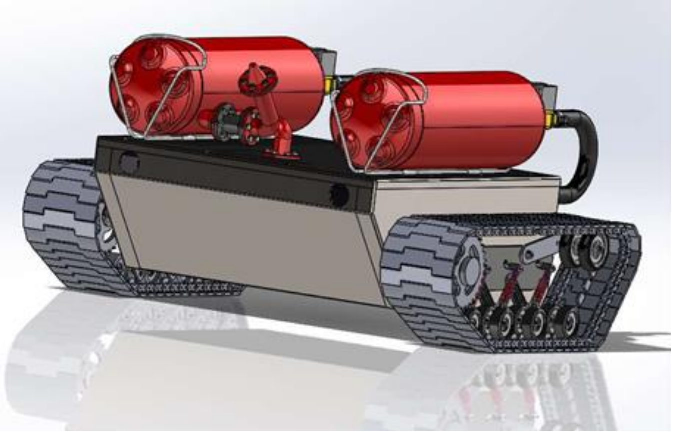


Figure 13: Final assembly of the Fire-Fighting robot.

III. Autonous navigation:

The Robot Operating System (ROS) is an open-source framework designed to facilitate the development and management of robotic applications. It offers a wide range of tools, libraries, and messaging systems that enable developers to create and integrate complex robotic systems[4]. After preparing the URDF file, we need to build a simulation environment to thoroughly test our robot's capabilities. For this purpose, we selected a paint products storage facility with dimensions of 30x15 meters. This environment contains shelves filled with paint boxes, providing a sufficiently complex layout to effectively evaluate the robot's performance in navigating and executing tasks under challenging conditions.

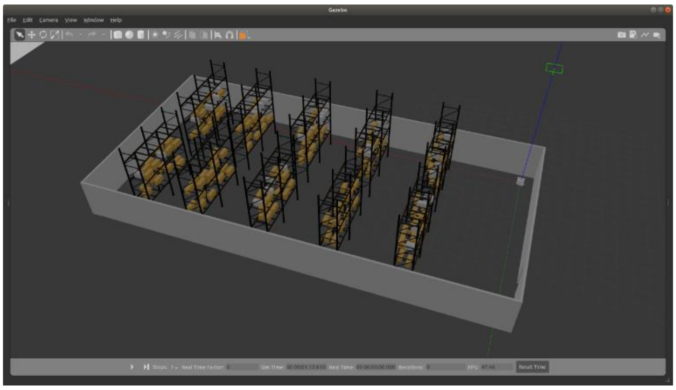


Figure 14: Simulation environment built using GAZEBO.

Once we builded the environment we need to create its map. The first step in the process was integrating a movement plugin to enable the robot to navigate the environment, ensuring it could reach every point within the space efficiently.

Next, we configured the LiDAR sensor to accurately scan the surroundings, allowing the robot to detect objects and define the areas where it could safely move.

Finally, we deployed a SLAM (Simultaneous Localization and Mapping) algorithm. SLAM is a technique that allows robots to create a map of an unknown environment while simultaneously tracking their location within it. Utilizing sensors like LiDAR, SLAM identifies key landmarks and continuously updates both the robot's position and the map as the robot moves[5]. Each time the sensor scans new areas, the map is refined, ensuring accurate navigation and environmental awareness.

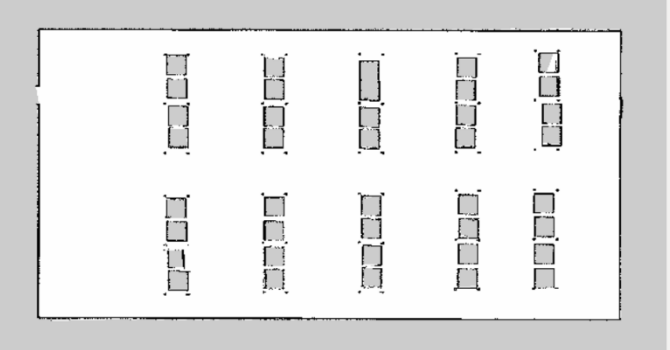


Figure 15: Map generated using SLAM.

Now we need to configure some parametrs before achieving autonous navigation:

Pre-built Map Loading: A pre-built map, typically created using SLAM, is loaded into ROS as an image and YAML file. This map is published to the /map topic, allowing the robot to reference its environment for navigation.

Localization Using AMCL: AMCL uses particle filtering to estimate the robot's position and orientation by comparing real-time sensor data to the pre-built map. Proper tuning of AMCL ensures accurate localization.

Path Planning: The move_base package manages both global and local path planning. The global planner creates a high-level route, while the local planner adjusts the path in real time to avoid obstacles.

Visualization and Goal Setting: RViz is used for visualizing the robot's position, sensor data, and planned paths. Users can also set navigation goals directly within RViz, which are sent to the robot for execution.

Configuring Move_base Parameters: Proper configuration of parameters related to motion, sensors, and costmaps is critical for smooth navigation. This includes tuning the base planner, costmaps, and trajectory parameters, all of which are defined in YAML files.

By configuring these components, you can create a robust and efficient autonomous navigation system in ROS.

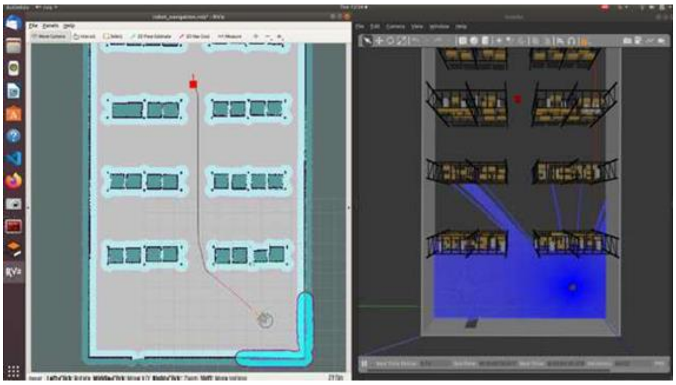


Figure 16 (a)

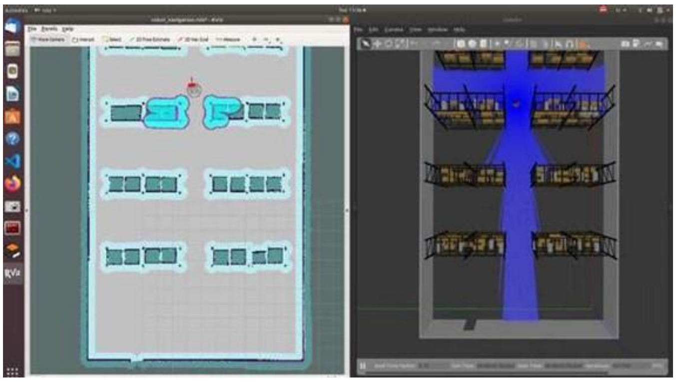


Figure 16 (b)

Figures 16(a) and 16(b) depict a simulation where the fire, shown as a red cube, has been detected. The robot uses the pre-generated map to choose the shortest path to the fire in a static environment, demonstrating efficient navigation. Additionally, if an unforeseen obstacle appears, the robot detects it in real-time and adjusts its path dynamically, ensuring it reaches the target safely and efficiently.

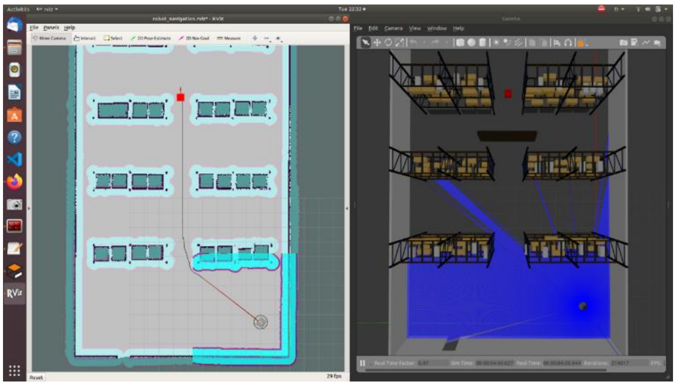


Figure 17 (a)

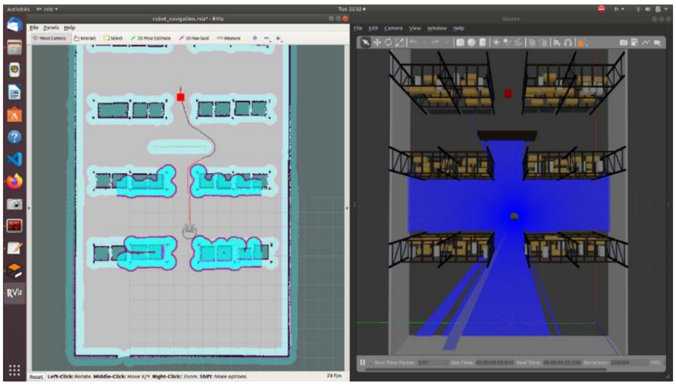


Figure 17 (b)

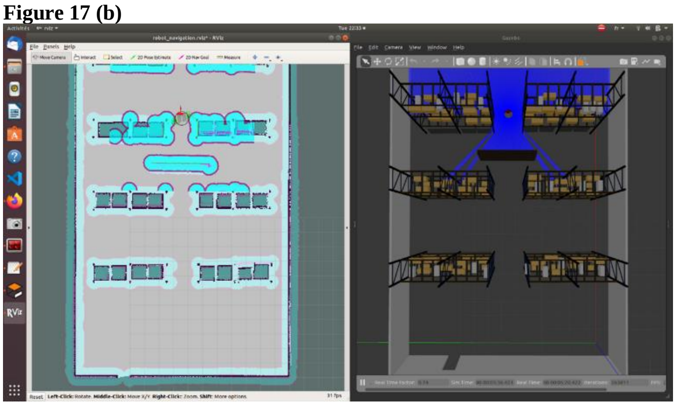


Figure 17 (c)

The previous figures (a, b, and c) illustrate a dynamic scenario where a new obstacle is introduced into the environment. In Figure 17(a), the obstacle appears in Gazebo but is not detected by the robot's sensors, so it follows the path based on the original map. In Figure 17(b), the robot's sensors detect the obstacle and begin calculating an alternative route. Finally, in Figure 17(c), the robot successfully avoids the obstacle and reaches its goal, demonstrating its real-time path planning and obstacle avoidance capabilities in a dynamic environment. This highlights the robot's ability to adapt to unexpected changes, ensuring safe and efficient navigation.

In this chapter, we explored the integration of the Robot Operating System (ROS) into our autonomous fire-fighting robot, showcasing how SLAM, AMCL, and the move_base package enable autonomous navigation, even in dynamic environments. Simulations demonstrated the robot's ability to detect and navigate around unforeseen obstacles while maintaining its path toward goals, highlighting the system's reliability and adaptability. Moving forward, further testing will refine the robot's capabilities, advancing its readiness for real-world firefighting applications. This successful integration marks a key milestone in our project.

IV. Conclusion :

This thesis presents the design and development of an autonomous fire-fighting robot, aimed at operating in hazardous environments where human intervention is risky. It began with a strong mechanical foundation, optimizing the chassis for durability, mobility, and balance. Tracked mobility provided stability across varied terrains, while the CO2 firefighting monitor enabled precise fire suppression in confined spaces.

The robot's intelligence was enhanced by integrating the Robot Operating System (ROS), transforming it into a smart, autonomous agent capable of mapping, navigating, and reacting to dynamic environments. Tools like Gazebo, RViz, and SLAM enabled simulations where the robot detected fires, avoided obstacles, and adapted in real-time.

This project demonstrates how combining mechanical engineering with advanced software creates a reliable autonomous fire-fighting robot, contributing to future real-world applications in fire safety. It highlights the potential for autonomous robots to reduce risks for firefighters and emergency responders, making a significant impact on fire disaster management**.**

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